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AUTOMATION OF LONG-PATH ABSORPTION CELL MEASUREMENTS

By

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June 1977

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Recent advances have been made in the operation of long-path absorption cells which make them easier to align and improve the accuracy of measurements made with them. Only one person is required now for routine measurements of low absorption coefficients of atmospheric absorbers that have significant impact on Army electro-optical systems. Unique gear designs for the adjustment of the cell mirrors are described which utilize low-torque linear drives and make possible rapid changes in pathlength and precision repositioning of the cell → next page

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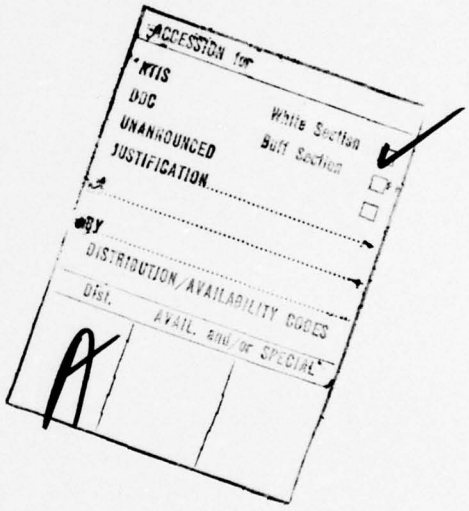
20. Abstract (cont)

output beam at long pathlengths. Automation of cell operation by the use of remote selsyn controls is described. Several techniques are discussed for precision optical alignment of long-path absorption cells, including the use of infrared radiation sources. The system accuracy which results from these refinements in operation is included.

PREFACE

The authors thank James B. Gillespie for his timely review of this report.



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INTRODUCTION

Army applications of electro-optical (EO) systems, especially high-energy lasers (HEL) and long-range laser and broadband systems, such as laser designators, range fingers, image intensifier and infrared imagers, remote wind sensors, etc., require a knowledge of low absorption coefficients of atmospheric constituents. An absolute measure of the weak absorptions (a few percent per kilometer or less) is difficult to obtain even with very sophisticated long-path absorption cells. Sometimes the concentration of weak absorbers can be increased to make measurement of the absorption coefficients easier [1]. However, self-broadening of gases [2] and even condensation, as in the case of water vapor [3], can severely limit how much the absorber concentration can be increased. Once an absolute measure of weak absorbers is obtained by using long-path absorption cells, spectrophones can be used to complement these measurements [4]. The basic problem then is obtaining the initial very accurate absolute measurement of the weak absorbers of interest and doing so in a timely fashion.

The Atmospheric Sciences Laboratory (ASL) has already made substantial improvements in its long-path absorption cell capabilities. Data acquisition and analysis have been automated [5,6], and techniques for reducing long-term system drift have been developed [7,8]. This report discusses system developments which improve the accuracy and fully automate long-path absorption cell measurements. In fact, only one person is now required to perform long-path absorption cell experiments. The savings in experimental man-hours as well as the improvement in measurement accuracy are quite significant.

BASIC CELL OPERATION

A detailed description of an absorption cell experiment is given elsewhere [9] as is the improved technique, path differencing [7], for obtaining data from long-path absorption cells by utilizing rapid changes in cell pathlength to minimize long-term drift error. The basic principles and procedures are described briefly here. Figure 1 gives the basic setup for a long-path absorption cell experiment using conventional White-type optics [10]. A source of radiation, in this case a laser, is divided into two portions by a beam splitter B. One portion goes to a reference detector system R. The other portion of the beam enters the absorption cell through a window W; makes multiple reflections from spherically concave mirrors M_1, M_2, and M_3; exits the cell through another window; and then goes to a sample detector system S. The pathlength in the cell can be determined by counting the number of reflection spot images in the multipath on mirror M_2 as seen through an observation window OW. A short multipath (1-spot) and a long multipath (N-spot) (Figure 2) are obtained by adjusting only mirror M_3 once mirrors M_1 and M_2 are appropriately positioned as described later.

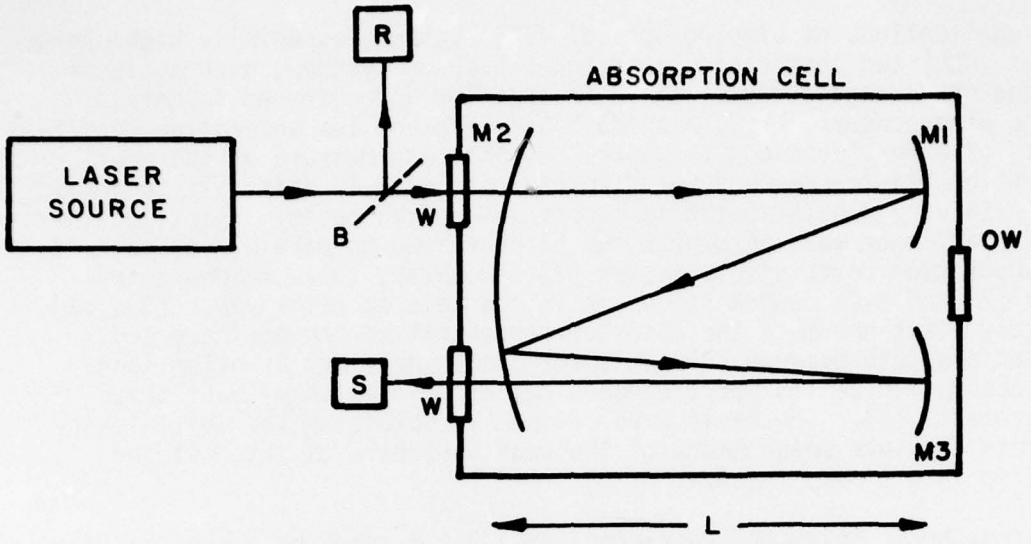

Figure 1. Conventional "White-type" absorption cell experimental setup: B, beam splitter; W, cell windows; OW, observation window; R and S, reference and sample detector systems; M_1, M_2, and M_3, spherically concave cell mirrors; and L, separation distance between cell mirrors.

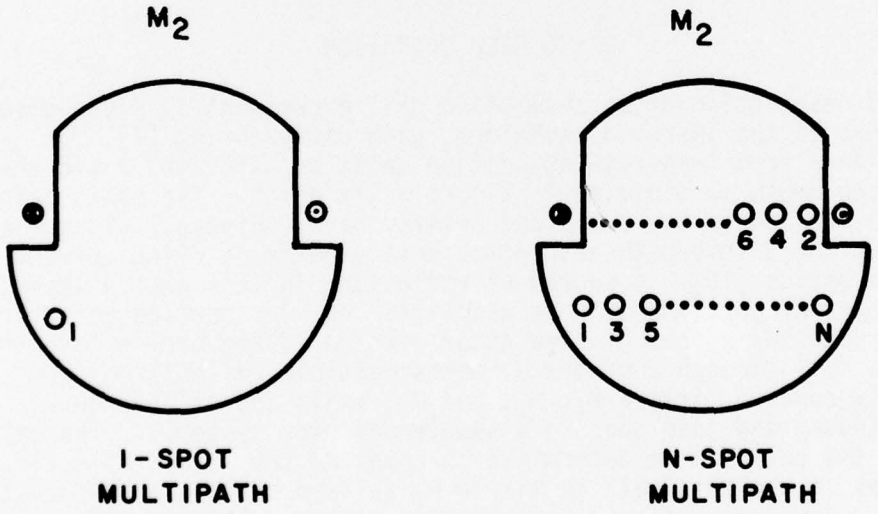

Figure 2. Views of mirror M_2 as seen from the observation window OW for a 1-spot (left) and an N-spot (right) multipath; numbered circles, images of laser source on mirror surface; circle with central dot, laser beam entering cell; and circle with "X," laser beam exiting cell.

Absorption coefficients of gases are measured by using a path differencing technique of rapidly taking reference and sample detector signal data for short 1-spot and long N-spot multipaths. Basically, absolute cell transmittance values for the optical path difference between an N-spot and 1-spot multipath are obtained by taking short-term time averaged ratios of relative transmittances (sample divided by reference detector signals) for the N-spot and 1-spot multipaths. The cell transmittance values obtained contain mirror reflectance loss and gaseous absorption contributions. Two such cell transmittance values are needed to obtain the absorption coefficient for a specific gas--one for a cell atmosphere with the absorbing gas and one without the absorbing gas. To obtain good accuracy in low absorption coefficient measurements, long-term drift error which plagues long-path absorption cells must be reduced. Path differencing which nearly eliminates long-term drift error requires rapid changes in cell pathlength, including precision beam positioning. Exact repositioning of the beams formed on mirror surfaces is essential in reducing long-term system drift. Long-path absorption cell optical systems designed to obtain maximum output beam stability by use of compensating optics [11] do so at the expense of mirror reflection loss reproducibility because the systematic cancelation of beam wander by the optical system inherently precludes the checking of exact beam positioning on the mirror surfaces.

CELL MIRROR ADJUSTMENT

A description of how the conventional White-type cell mirrors are mounted in a long-path cell is required before their adjustment is discussed. The optics of the ASL 21-m stainless steel absorption cell will be used here and throughout this report as a representative example of a long-path cell optical system. The mirror holders and mechanism for attachment to the 21-m cell are adaptations of the mirror system used in a 2-m stainless steel cell purchased from Boller-Chivens (Contract No. DAAD07-71-C-0254). Figure 3 illustrates the basic components of the 21-m cell system. The mounting rings (one in each end of the cell), which support the cell mirror holders and mirrors, are secured to the cell wall by a set of pressure plates and bolts. Each mirror holder is attached to the mounting ring on two large threaded bolts and secured by pairs of nuts, which makes possible positioning of the mirror holders along the length of the cell.

The mirror holders are more complex. They consist of three parts which are connected together (the first to the second and the second to the third) by two sets of spring-loaded flexures. These flexures allow rotation of the mirror-holding portion of the mirror holder about the vertical and horizontal axes of the mounting ring by moving two pressure rods in or out along the length of the cell. The two-mirror-end pressure rods are linear motion feedthroughs which push against contact plates and are attached to the two-mirror end flange of the cell by a flanged vacuum bellows. This allows the mirror holders to be adjusted from outside the evacuable cell. The single-mirror-end pressure rods are

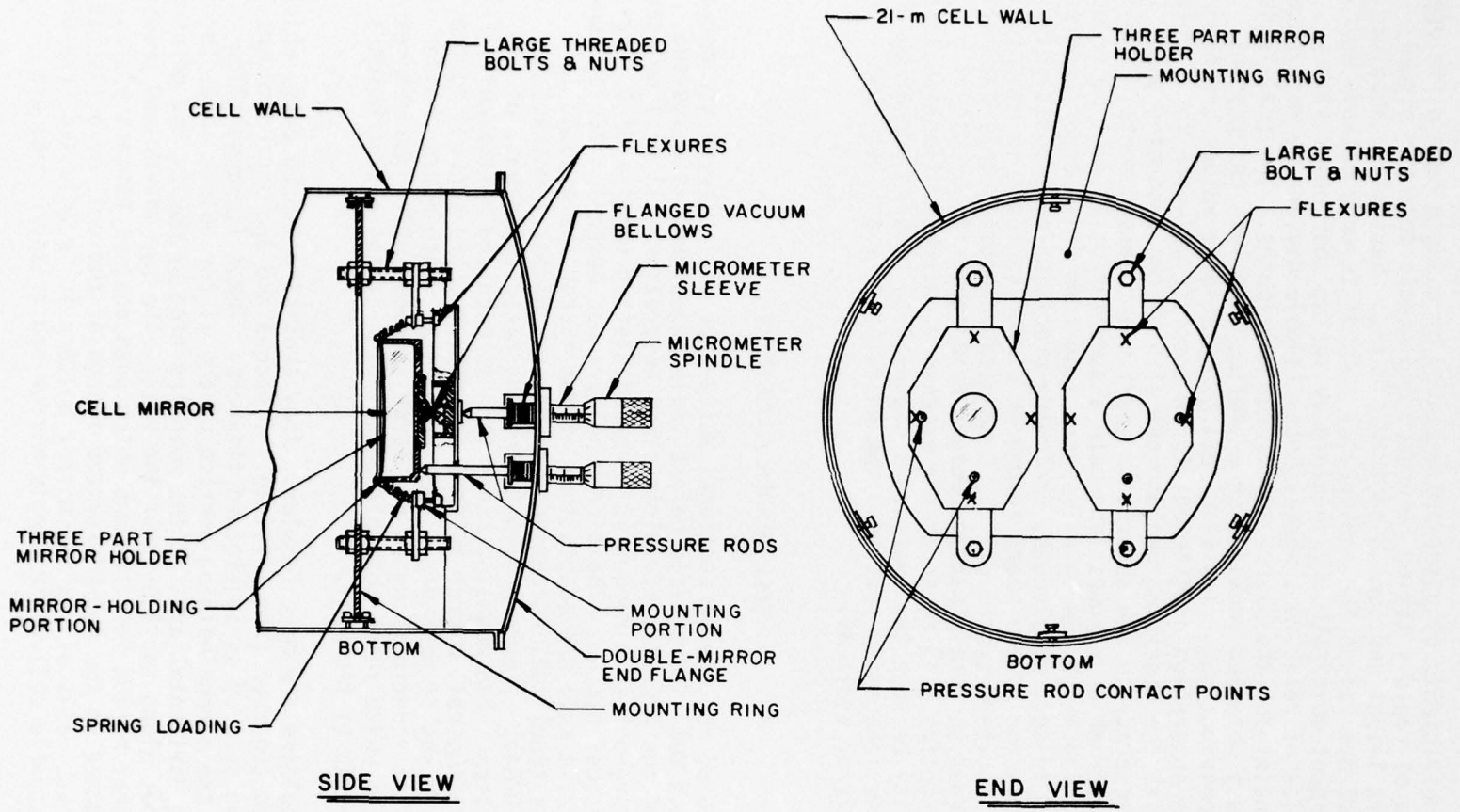

Figure 3. End and side views of mounting ring, three-piece mirror holders with spring loaded flexures, and double-mirror end cell flange with flanged vacuum bellows and pressure rods.

threaded into the mounting portion of the mirror holder and are initially positioned inside the cell. Additional adjustment of the single mirror is not needed.

The optical system for a conventional White-type absorption cell consists of three spherically concave mirrors, one at one end and two at the other end of an absorption cell as in Figure 1. The radii of curvature of all three mirrors and the separations between the single mirror and either of the two mirrors at the opposite end of the cell are all of equal length L. This forms a beam conserving system. The f-number of the entrance beam into the cell is adjusted, by a pair of concave mirrors placed between the laser and the beam splitter in Figure 1, to focus the beam in the plane of mirror M_2 and to irradiate a large portion of the mirror M_1. Mirror M_1 focuses the beam onto mirror M_2. The reflected beam diverges to fill a large portion of mirror M_3 and then refocuses in the plane of mirror M_2 as it passes out of the absorption cell.

The above optical configuration does not give the best beam conservation. Focusing on the surface of mirror M_2 can greatly accentuate the effects of mirror imperfections such as a speck of dust or small pit in terms of mirror reflection losses and reproducibility. To avoid such degradation, a collimated beam a few millimeters in diameter is introduced into the cell. Mirror M_1 focuses the beam midway along the length of the cell, and mirror M_2 sends a collimated beam to mirror M_3 which in turn focuses the beam midway along the length of the cell. The cell output beam (circle with "X") thus becomes a diverging beam of the same diameter as the input beam (circle with dot) upon leaving the cell. This configuration limits the maximum obtainable pathlength of the cell because the spots on mirror M_2 are not focused to a small diameter; but no beams are focused on mirror surfaces, which results in far better beam conservation [7].

The initial positioning of mirror M_2 with respect to mirrors M_1 and M_3 is important. To begin, the input beam has its f-number adjusted as in the first case above, so that the input beam is focused inside the absorption cell just off the input window upper right edge of mirror M_2 and in the plane of its reflecting surface as shown in Figure 2. The diverging beam from this focal point is then centered on the surface of mirror M_1. Mirror M_1 is adjusted to focus the reflected beam directly below the output window upper left edge of mirror M_2, again shown by spot 1 in Figure 2. If the beam does not focus on the surface of mirror M_2, then the separation distance between mirrors M_1 and M_2 is not equal to their radii of curvature. Mirror M_1 must be repositioned and the above procedure repeated until the beam from mirror M_1 focuses at the surface of mirror M_2. The diverging beam from the surface of mirror M_2 is then centered on the surface of mirror M_3 by adjusting mirror M_2 about its horizontal and vertical axes. Mirror M_3 may need to be moved closer to or farther from mirror M_2 if its return beam does not also focus at the surface of mirror M_2. This adjustment maximizes the obtainable pathlength and minimizes the chance of beam clipping inside the absorption cell. This is true whether the input beam is focused in the plane of mirror M_2 or a collimated input beam is used.

After initial positioning of the cell mirrors, the absorption cell can be sealed and used for measurements. To obtain maximum pathlength, the collimated input beam is positioned as close to the upper right edge of mirror M_2 as possible without causing clipping and is also centered in the middle of mirror M_1. The adjustment of mirror M_1 is critical for obtaining maximum pathlength and allowing rapid changes of the pathlength from 1- to N-spot multipaths with only mirror M_3. The spot 1 in Figure 2 is positioned so that it is centered directly below the left edge of mirror M_2 and an equal distance below the horizontal optical axis of mirror M_2 as the exit spot with the "X" is above the axis. The latter adjustment is performed in conjunction with vertical adjustments of mirror M_3. The 1-spot multipath output beam can be centered on the sample detector by adjusting mirror M_3. If horizontal adjustment of the mirror M_3 does not produce a long N-spot multipath output beam which is centered vertically on the sample detector system, the spot 1 on mirror M_2 must be appropriately raised or lowered by adjusting mirror M_1 with corresponding vertical adjustment of mirror M_3 until both the 1-spot and N-spot outputs are centered on the sample detector.

In practice, the multipath outputs must be repositioned horizontally and vertically to within 1 mm for a 1-spot to 37-spot path difference. This path difference represents a pathlength of 1,512 m for the 21-m absorption cell (i.e., 2(N-1)L). This puts restrictions on how precise the smallest adjustment of the linear feedthrough pressure rods must be. The contact points of the pressure rods and mirror holders are 114 mm from the corresponding axis of rotation. A small angular rotation of mirror M_3 will cause a corresponding angular offset of the output beam of twice the rotation angle for each reflection from mirror M_3 or 2[(No. of spots + 1)/2] = No. of spots + 1. Hence, to obtain 1 mm repositioning error for a 37-spot output requires a linear motion error (x) of the pressure rods of

$$38 \left(\frac{x}{114\ \text{mm}}\right) = \left(\frac{1\ \text{mm}}{21{,}000\ \text{mm}}\right)$$

or x = 0.000143 mm or 0.143μm. In addition, to be able to rapidly change pathlengths between 1- and N-spot mutlipaths requires the movement of the output beam for the 1-spot multipath (makes only one reflection from mirror M_3) a distance of 279 mm in the plane of mirror M_2 to the spot 2 position in a 37-spot multipath. The corresponding linear motion (y) of the pressure rod controlling the vertical axis rotation is

$$2 \left(\frac{y}{114\ \text{mm}}\right) = \left(\frac{279\ \text{mm}}{21{,}000\ \text{mm}}\right)$$

or y = 0.757 mm.

Initially, the pressure rods were adjusted by using bakeable linear motion feedthroughs Ultek (Perkin Elmer) Model 282-6200 with 1.57 thread/mm micrometer spindle drive and accuracy of 0.127 mm including backlash. To meet the requirement y of rapidly changing pathlength was trivial;

a little over one revolution of the spindle was necessary. Meeting the requirement of rapidly obtaining the repositioning of the output for a 37-spot multipath was nearly impossible because the magnitude of the repositioning error of the micrometer was about one thousand times that required to meet the x repositioning demands. Two major problems were inherent in the system, excluding the minor problem of gear backlash. First, the torque required to obtain the drive accuracy needed was too small for direct manual micrometer operation; and second, the drive controls for the system were at one end of the 21-m cell, whereas the cell output had to be viewed from the opposite end.

NEW ADJUSTMENT CONTROLS

Both of the above problems have been eliminated through use of a new drive gear design and remote selsyn (or synchronous) motors; and yet, the ability to rapidly change pathlengths between 1- and 37-spot multipaths was retained. First to be addressed is the problem of spindle torque. Several system components were added to the end of the cell to allow control of the pressure rods from outside a 20 cm thick heating shell which is around the entire cell for bakeout and temperature control purposes. These changes are depicted in Figure 4. A 1-1/4-cm thick aluminum base plate was offset from the cell's two-mirror end flange by several 2-1/2-cm diameter bolts. This plate was used to rigidly hold all gears required to make fine adjustments of the four pressure rods. The linear motion feedthroughs were used but without the spindle attached. An extension rod was threaded into the end of the pressure rod instead. A Starrett micrometer Model 262RL with 1.57 thread/mm was attached to the end of the extension rod and mounted to the outside of the aluminum plate. The operation of the micrometer was altered. The spindle was secured to the drive rod by tightening the end nut after the rachet was removed. The allen bolt which screws into the guide slot in the drive rod was removed to allow the drive rod to rotate freely in the mounting sleeve when the spindle-drive rod unit (which includes the spindle attached to the drive rod) is threaded onto it. The result is a micrometer drive which, when the mounting sleeve is rotated, a nonrotating drive of the spindle-drive rod is obtained with only micrometer drive thread slop. Even this problem was eliminated by spring loading the pressure rod extension against the linear motion feedthrough sleeve.

The problem of the small torque required to fine position the micrometer drive was alleviated by a precision worm gear operated 25:1 reduction gear mounted directly to the aluminum plate and secured to the Starrett micrometer sleeve. Again, no rotation slop of the reduction gear was encountered because the whole drive mechanism is spring loaded against the linear motion feedthrough sleeve. There is a little slop in the worm gear, but no corresponding linear motion of the pressure rod results. With this new drive gear design a 1-degree rotation of the worm gear results in a pressure rod drive of 0.0706μm, which is quite adequate for the precision repositioning of the long-path output beam.

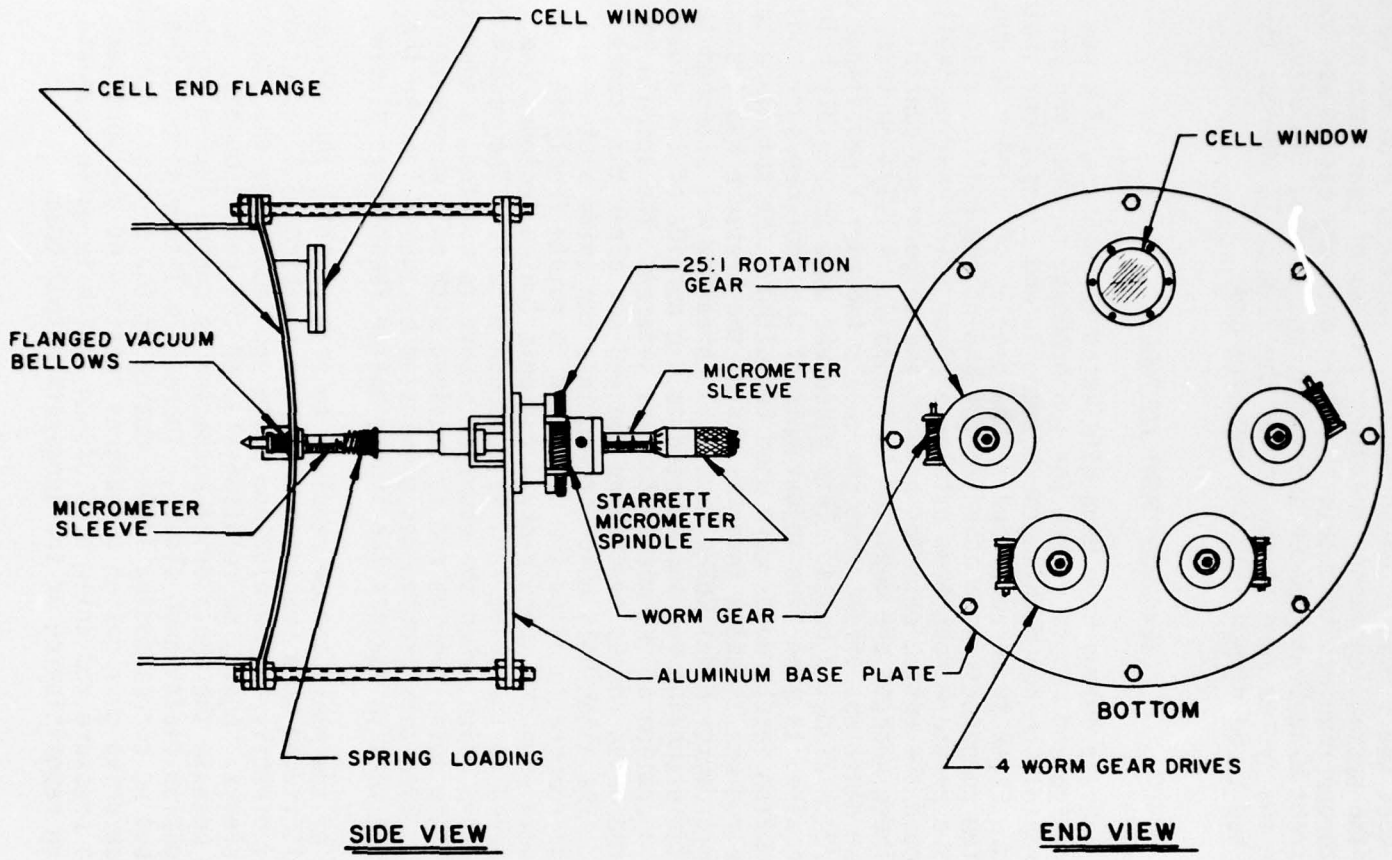

Figure 4. Aluminum base plate (end and side views) with attachment to the double-mirror end cell flange, new low-torque micrometer drive, and spring loaded attachment of the new drive to the old pressure rod and vacuum bellows arrangement.

The problem of remote control will now be addressed. Basically a selsyn transmitter and receiver are used to obtain 1:1 remote drive of the worm gear on the low-torque micrometer drive system (Figure 5). The selsyn transmitters are controlled by a 7-cm diameter dial graduated in degrees. The transmitters are located at the single-mirror end of the absorption cell where the cell output beam can be adjusted and observed simultaneously. The procedure for aligning and changing cell pathlengths will be discussed later, but the mechanical requirements for rapid remote changes between a long and short multipath will be discussed now. For changing from a 1- to a 37-spot multipath in the 21-m cell, the pressure rod must be driven 0.757 mm or 29.8 revolutions of the worm gear controlling rotation of mirror M_3 about its vertical axis. This is impractical for rapid pathlength changes. Two step-up gears are used to alleviate this system operation problem. First, a 1:4.75 step-up gear is used between the worm gear and the selsyn receiver to reduce the fine adjustment of the remote control of the linear pressure rod drive to 0.318μm per degree rotation of the selsyn transmitter dial. Obtaining the required 0.143μm linear drive precision is still routinely possible. Next a coarse adjustment dial is attached to the selsyn transmitter fine adjustment dial by a 1:5 step-up gear. As a result, only a little over one revolution of the coarse adjustment dial is required to make the 1- to 37-spot multipath change since the total gear step-up over the worm gear drive is 1:23.75. By use of this arrangement, both remote beam positioning and rapid pathlength change requirements are satisfied.

LASER ALIGNMENT

The alignment of any optical system containing light sources is greatly facilitated when the sources are of visible wavelengths. This is especially true for the precision alignment required to perform long-path absorption cell experiments. A cw helium-neon (He-Ne) laser is usually used to obtain the optical system alignment required. The light source of interest, which in the case of most EO and HEL systems is in the infrared and hence is invisible to the naked eye, is then made to propagate colinear with the He-Ne laser.

A detailed setup of an experiment using a 21-m stainless steel White cell and a line tunable pulsed deuterium fluoride (DF) laser source (Figure 6) will be used to illustrate the types of problems encountered in making long-path absorption cell measurements [9]. A Lumonics Model TEA-201 pulsed (0.3 Hz), line tunable, DF laser is used which has an unstable resonator front reflector and a grating back reflector for line selection. The resulting output is donut-shaped in the near field and has a central maximum diffraction ring pattern in the far field (25 m away) where the beam is collected by a spherically concave mirror CM_1. The He-Ne alignment laser is made colinear with the DF laser by use of several flat mirrors M and one mirror M' with a 1-cm diameter hole drilled through the center to allow the He-Ne beam to pass through. The donut-shaped DF beam with an outside diameter of 4 cm and inside diameter of 2 cm is centered on mirror M' about the central hole by using a sheet of

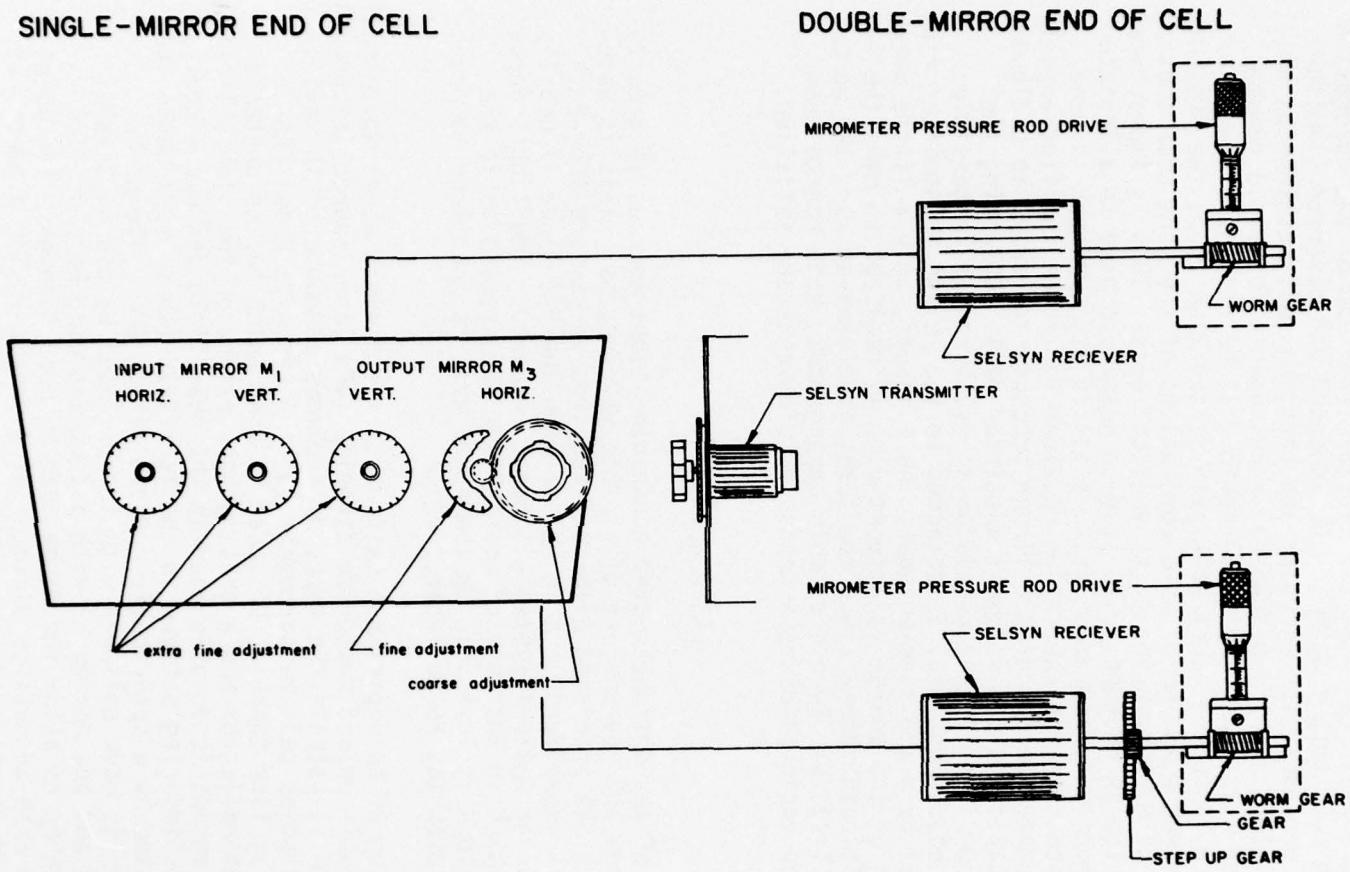

Figure 5. Remote selsyn transmitter and receiver arrangement including both the 1:1 and the stepped-up gear drives.

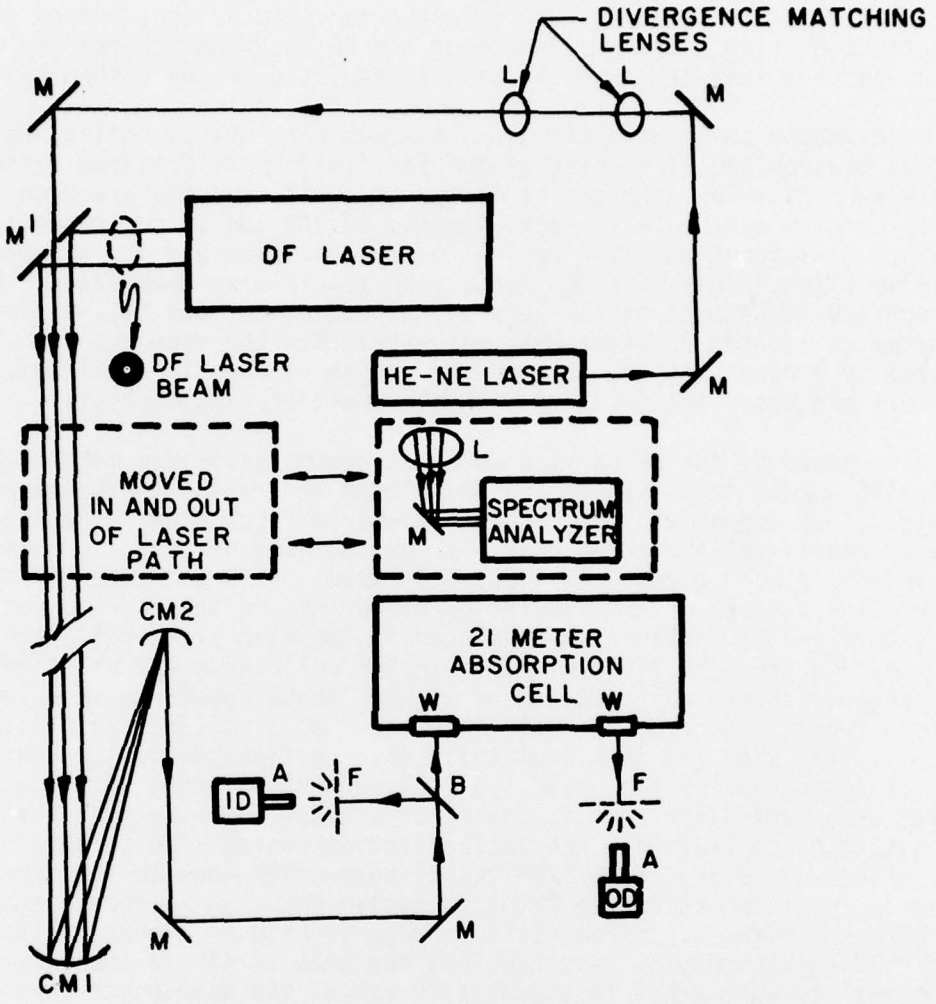

Figure 6. Experimental setup for an experiment using a DF laser source and the ASL 21-m absorption cell: He-Ne alignment laser with adjustment mirrors M; L, divergence matching and focusing lenses; M', special mirror with central hole; spectrum analyzer; CM_1 and CM_2, collection and collimating spherically concave mirrors; B, 2-mm thick calcium fluoride beam splitter; F, Teflon diffuse transmittance filters; A, detector apertures; and ID and OD, input and output indium antimonide detectors, respectively.

high sensitivity Edmund Scientific Company liquid crystal. The mode quality of the DF laser was checked by focusing the 4-cm diameter near-field beam with a calcium fluoride lens L to a few millimeters in diameter and observing the focused beam on the liquid crystal. The laser front reflector and grating were adjusted to yield a donut-shaped pattern of uniform heating. The wavelength of the DF laser was checked by inserting a spectrum analyzer into the beam as depicted in the dashed box.

A 5-mm diameter collimated DF laser beam was obtained by collecting the central maximum and first ring of the far-field DF diffraction pattern with a 4-cm diameter aperture at mirror CM_1. CM_1 and CM_2 are both spherically concave mirrors with focal lengths of 160 and 20 cm, respectively. They are positioned on a 2-m optical bench approximately 180 cm apart and only slightly off-axis to the DF beam to minimize aberration. By appropriate adjustment of the separation between CM_1 and CM_2, a 5-mm diameter collimated DF laser beam was obtained. The beam quality was checked by propagating the DF beam the length of the 21-m cell outside the cell and observing its size with the sheet of liquid crystal.

The divergence of the DF and the He-Ne alignment laser was matched by inserting a beam telescope in the He-Ne beam before the two beams were combined. By adjustment of the beam telescope focus, the He-Ne beam was made as nearly collimated as possible for the separation between mirrors CM_1 and CM_2, which gives a collimated DF beam. Several rings of an He-Ne diffraction pattern were collected by mirror CM_2 in this configuration. Two 1-cm diameter apertures were placed in the beam after reflections from CM_2 and from the first mirror M in the collection optics. The He-Ne diffraction pattern was centered on each of these apertures to ensure uniform repositioning of the cell input beam on a routine basis. The beam splitter used (B) is a 2-mm thick calcium fluoride flat which causes minimal separation of the He-Ne and DF laser optical axes due to wavelength dependent difference in their refraction by the optical flat. It is best to use a flat with one antireflection coated side to obtain only one reflected (in this case a DF laser) beam which goes to the input detector ID of the reference detector system and also to reduce etalon interference effects. If an optical wedge is used as a beam splitter, a matched pair should be inserted into the beam at 45° to the beam and orthogonal to each other to essentially cancel the wavelength dependent refraction effects. Care must be taken in selection of an appropriate beam splitter so as not to alter the colinearity of the He-Ne and DF lasers because of the exacting requirements of long-path absorption cell optical alignment.

The two beams which go to the input (ID) and output (OD) detectors of the reference and sample detector systems are centered on cross hairs on specially selected diffuse transmittance filters F (diffuse reflectors could also be used). For the case of DF, Millipore LSWP04700 Teflon membrane filters have relatively flat forward lobe diffuse transmittance and work well as diffusers of DF radiation reducing the effects of beam jitter and wander. Apertures A are used to select a small enough solid angle of the diffused laser beam to ensure linear detector response.

Additionally, the He-Ne alignment beam diffraction pattern can be seen through the filter, which makes repositioning easier. The colinearity alignment is performed on the output beams which pass through the cell output window before they reach the sample diffusing filter. A short focal length spherically concave mirror is inserted into the beams, and they are focused onto an activated charcoal block (typically used in spectrum analyzers). The focused pulsed DF laser beam causes a bright burn pattern on the charcoal block which is centered on the focused He-Ne diffraction pattern (slight adjustments of the cell input mirror M may be needed to ensure a uniform intensity He-Ne diffraction ring pattern at long cell pathlengths). This adjustment is performed for each change to the long N-spot multipath and once performed ensures colinearity for all shorter multipaths. The pathlength is determined by counting the number of image spots which cross the output cell window by observing the He-Ne laser beam on the membrane filter between the 1- and N-spot multipaths. Again a pair of selsyn transmitters and receivers is used to perform remote adjustments of the micrometers of mirror M' from the single-mirror end of the absorption cell (Figure 7).

Finally, the initial positioning of the multipath spot 1 will be discussed. The spot 1 is centered on the upper right edge of mirror M_2, and its semicircle output beam vertically centered on the horizontal membrane filter cross hair by adjusting mirror M_1. The distance which the spot 1 must be lowered by mirror M_1 to allow pathlengths to be changed from a 1- to an N-spot multipath using only vertical axis rotation of mirror M_3 is determined as discussed before. Each time a series of data is taken, the spot 1 is lowered the same distance to ensure exact repositioning of the spot 1 on mirror M_2.

REPRODUCIBILITY OF MEASUREMENTS

The elaborate alignment procedures and techniques to decrease the time required to change cell pathlengths are used to obtain very accurate absorption coefficient measurements with the path differencing technique. Of paramount importance to the success of path differencing is obtaining a short-term time average of the cell mirror reflectance loss for the path difference between a 1- and N-spot multipath. Data were taken over a 2-month time interval on 26 DF laser lines ranging from $P_{1\_0}(2)$ at 3.5μm to $P_{3\_2}(11)$ at 4.0μm for a reference gas filled cell of 760 torr of an 80/20 mixture of N_2/O_2 which is essentially nonabsorbing except near 4.0μm. The transmittance values for a 1.512 km path difference between a 1- and 37-spot multipath ranged from 0.11 to 0.17. Three sets of short-term path differencing time averages were taken for all 26 DF laser lines separated by a few weeks. The short-term time averages exhibited typically less than 2% error for eight path differences values. The long-term drift error was typically around 1/2% for the three data sets, which indicates very little systematic error. If a large number of short-term time averages are taken for a single laser line, the long-term reflectance loss may contain less than 1/2% error. Even with the

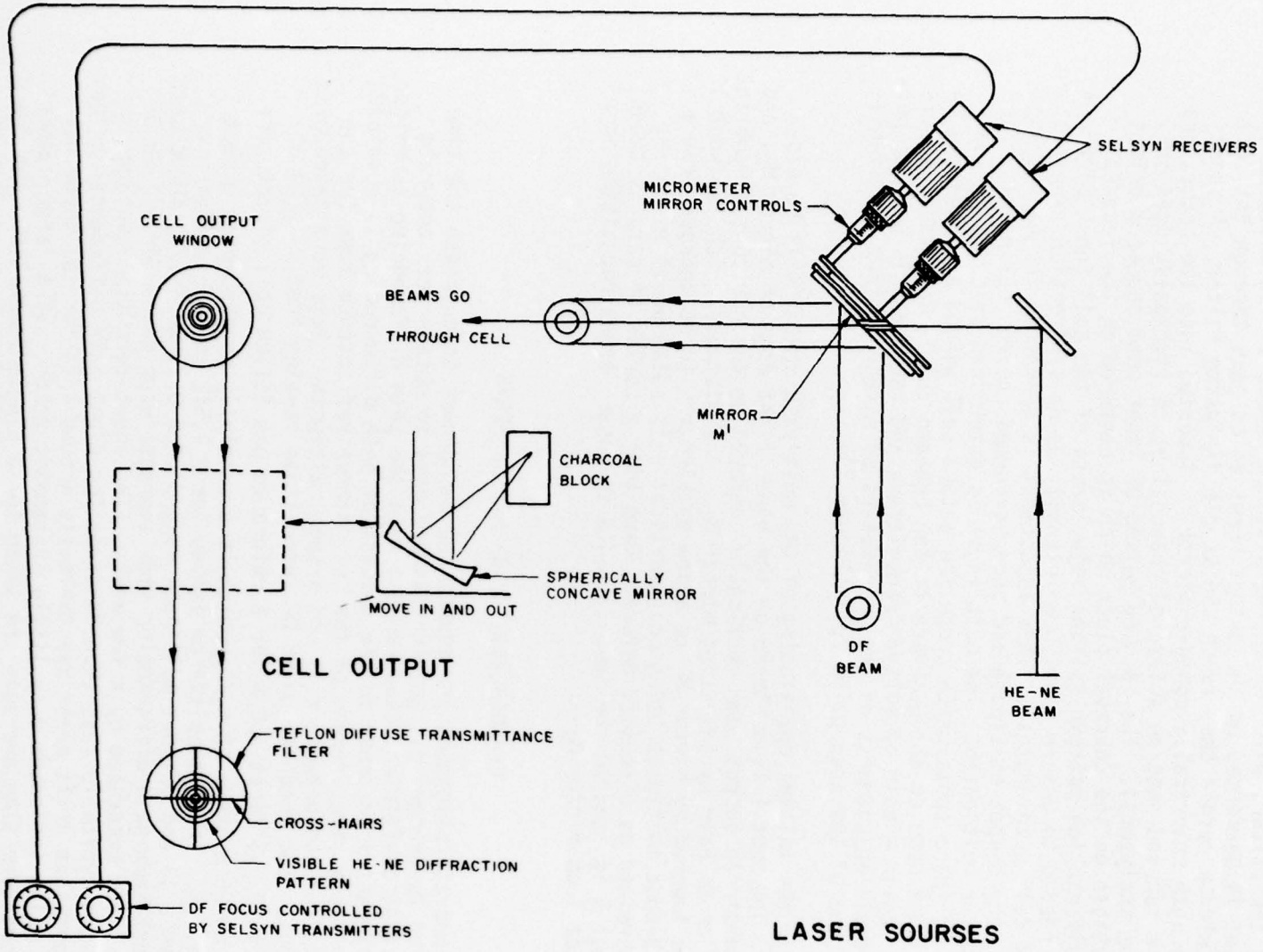

Figure 7. Output beam alignment scheme using He-Ne diffraction pattern, charcoal block, and remote selsyn controls of the special mirror M' with the central hole.

1/2% transmittance measurement accuracy for a 1.512 km path difference, absorptions of a few percent per kilometer have already been made [12].

CONCLUSION

Several improvements have been made in long-path absorption cell measurement capabilities which enable a single person to operate a 21-m White cell and obtain state-of-the-art measurement accuracy. Among the improvements are the low-torque linear drives for vacuum feedthrough pressure rods, remote operation for cell mirror adjustment and laser alignment using selsyn transmitters and receivers, and a variety of detection and alignment techniques. These improvements have extended the capabilities of long-path absorption cells, so that timely measurements of low absorption coefficients such as the water vapor continuum at room temperature between 3.5 and 4.0μm are now routine. Some of the techniques discussed may also be very useful in other measurement fields.

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